ENERGY TECHNOLOGIES AREA

LAWRENCE BERKELEY NATIONAL LABORATORY

Energy Analysis &
Environmental Impacts Division

Reversible Fuel Cell Cost Analysis

FC332

DOE FCTO 2020 AMR Update

April 30, 2020

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Overview

Timeline

- Project Start Date: Nov 1, 2018
- Project End Date: Nov. 30, 2020
- Percent complete: ~50%

Budget

- FY19 DOE Funding: $ 200,000
- FY20 Planned DOE Funding: $ 150,000
- Total DOE Funds Received to Date: $350,000

Barriers Addressed

- The extent to which **hydrogen energy storage costs can be reduced** by consolidating electrolyzers and fuel cell stacks **in a unitized, reversible fuel cell.**
- The role of **hydrogen for long term energy storage** to support greater fractions of variable renewable electricity

Partners

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Relevance (motivation)

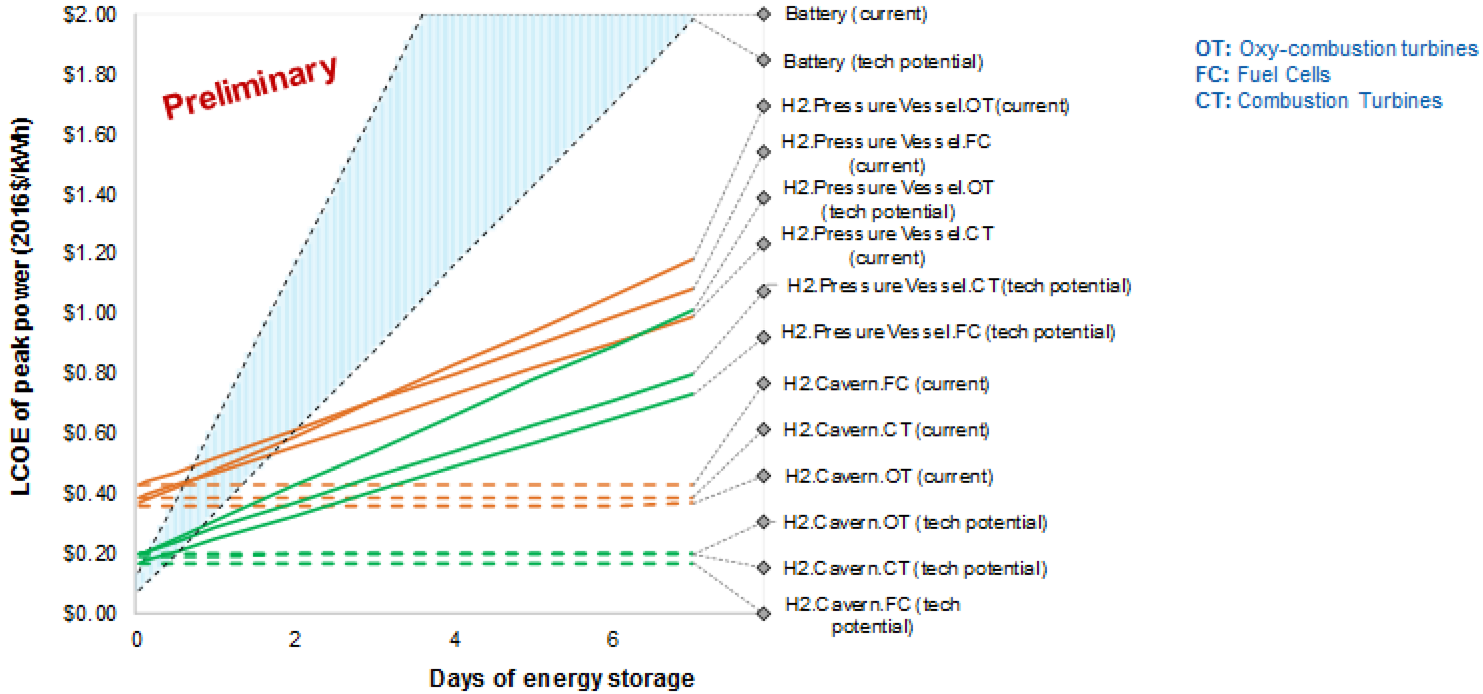
Relevance/ Objective

Hydrogen technologies could play a key role in providing easily dispatchable power to address resiliency, grid support, and microgrid needs. **Unitized reversible fuel cells,** together with hydrogen storage, could form an energy storage system that can provide long duration energy storage that is cost competitive with other technologies.

- The project objective is to investigate the competitiveness of RFCs for energy storage in a few key applications as a function of use-phase conditions and parametric cost assumptions
- The project will determine technical targets for reversible fuel cells with a focus on large scale energy storage for grid support
- The project will develop a parametric cost model for RFCs based largely on existing cost studies

At ~10h of storage, hydrogen technologies are more cost competitive than batteries

Ref: H2FAST Benchmark vs. Storage Days (NREL Penev et al., 2019)



Round trip efficiency limitations are surpassed by **lower cost storage** benefits:
At ~10h of storage, hydrogen technologies are more cost competitive than batteries.

Motivation – Chemical storage can have very low energy storage costs ($/kWh) compared to other approaches

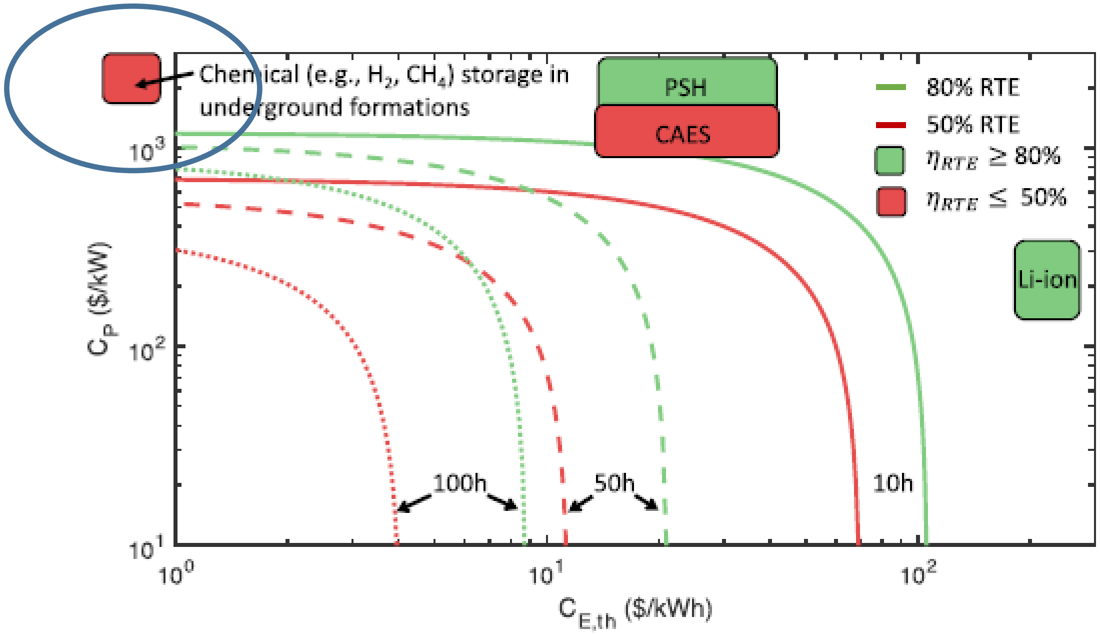


Figure 3. Relationship between Power and Energy Capital Costs Derived from Figure 2

Albertus et al 2020

Motivation – how to sharply reduce capital cost for power conversion units ($/kW) for chemical storage (H2)?

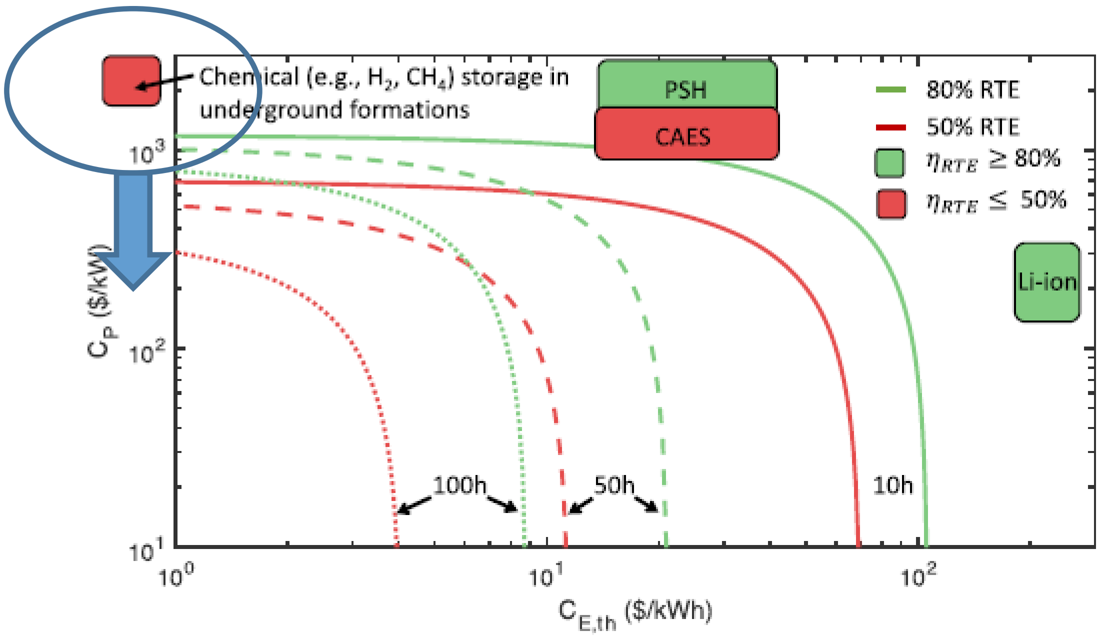
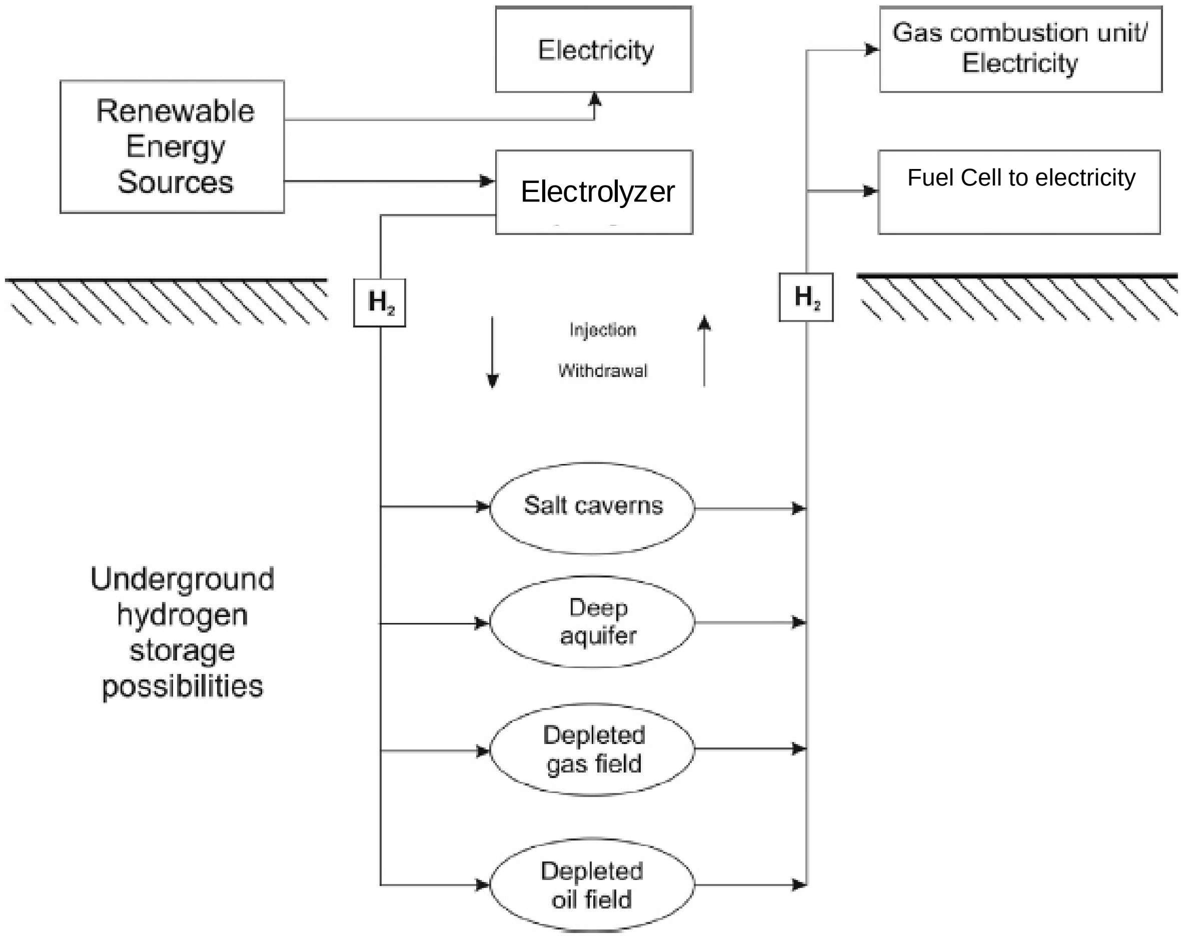


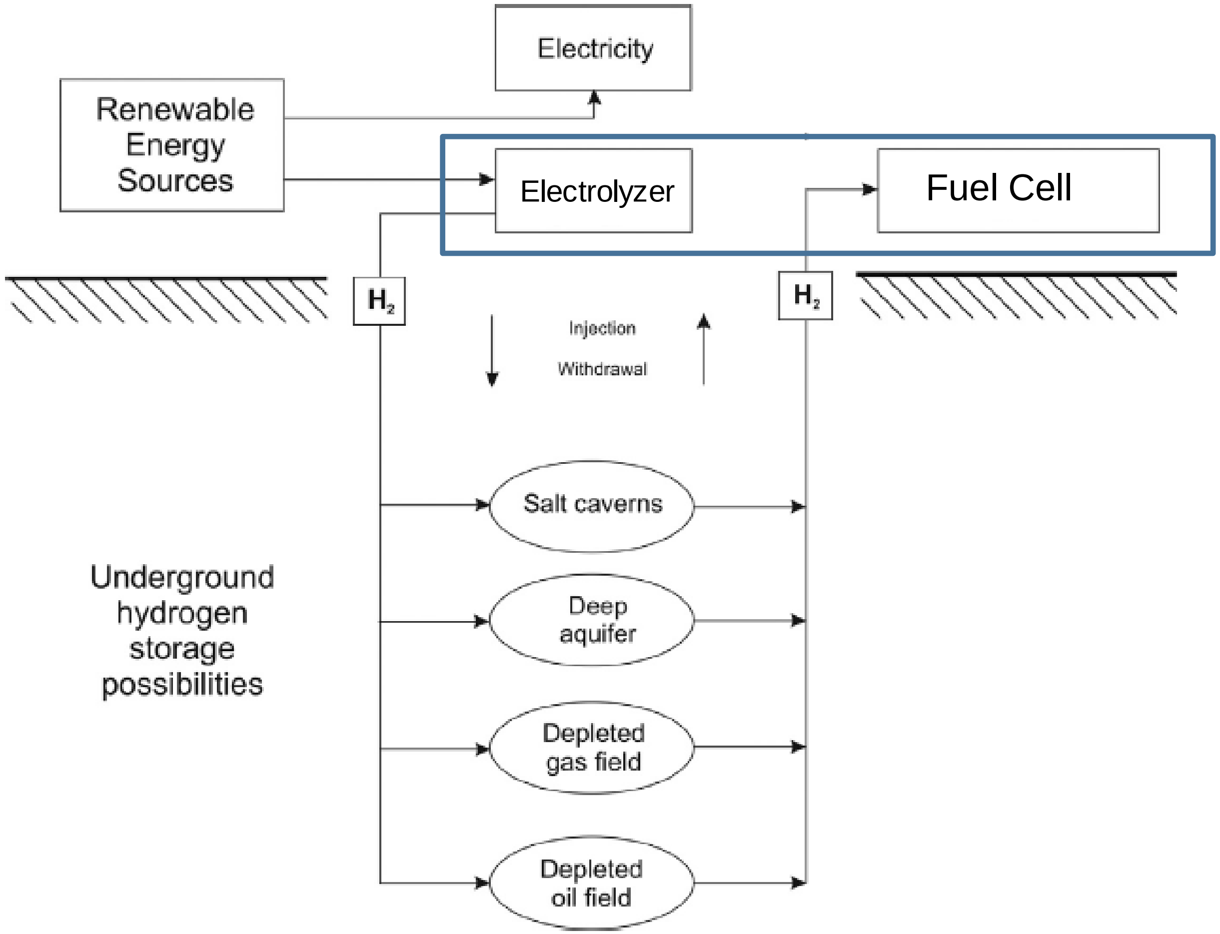
Figure 3. Relationship between Power and Energy Capital Costs Derived from Figure 2

Albertus et al 2020

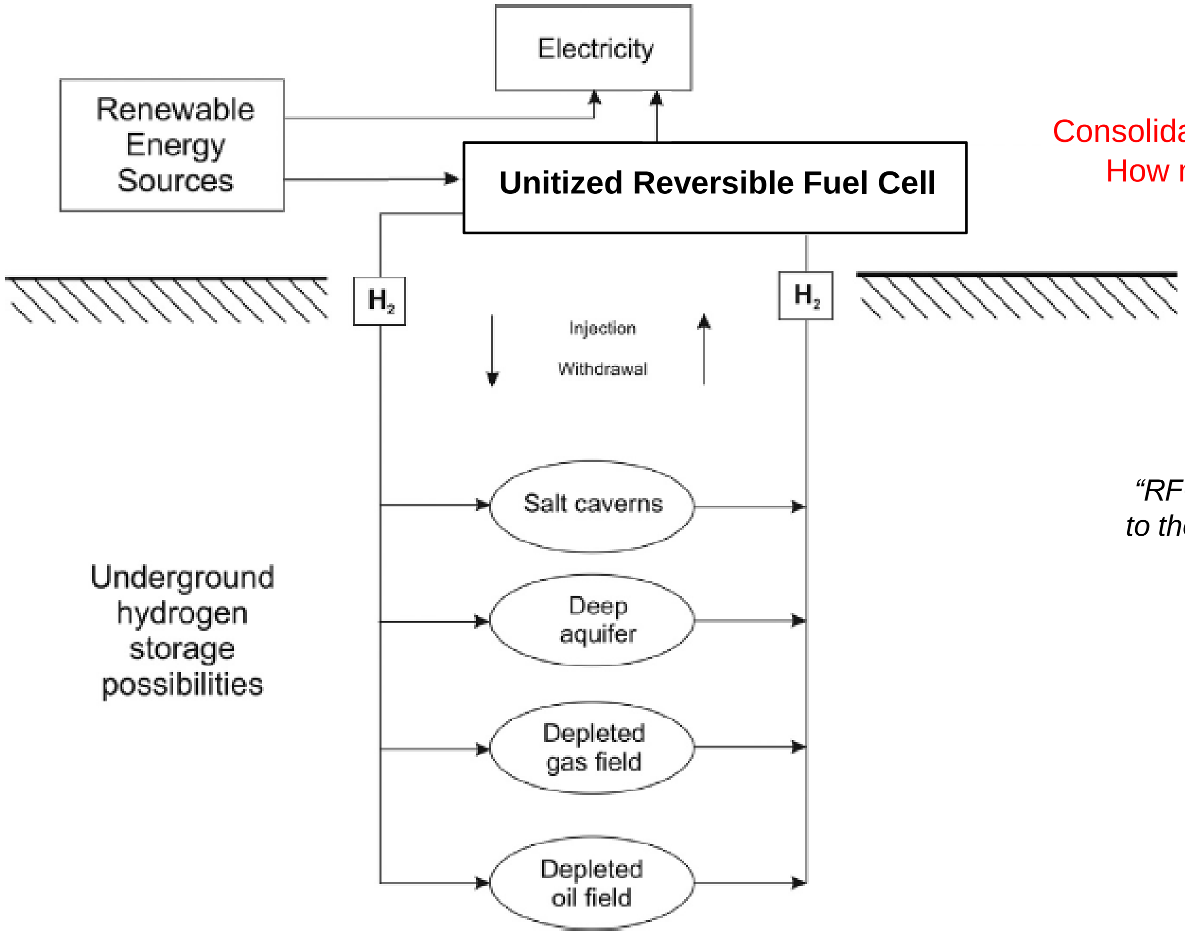
Grid-scale H2 Storage system schematic



Consolidate Electrolyzer and Fuel Cell to unitized stack for capital cost reduction



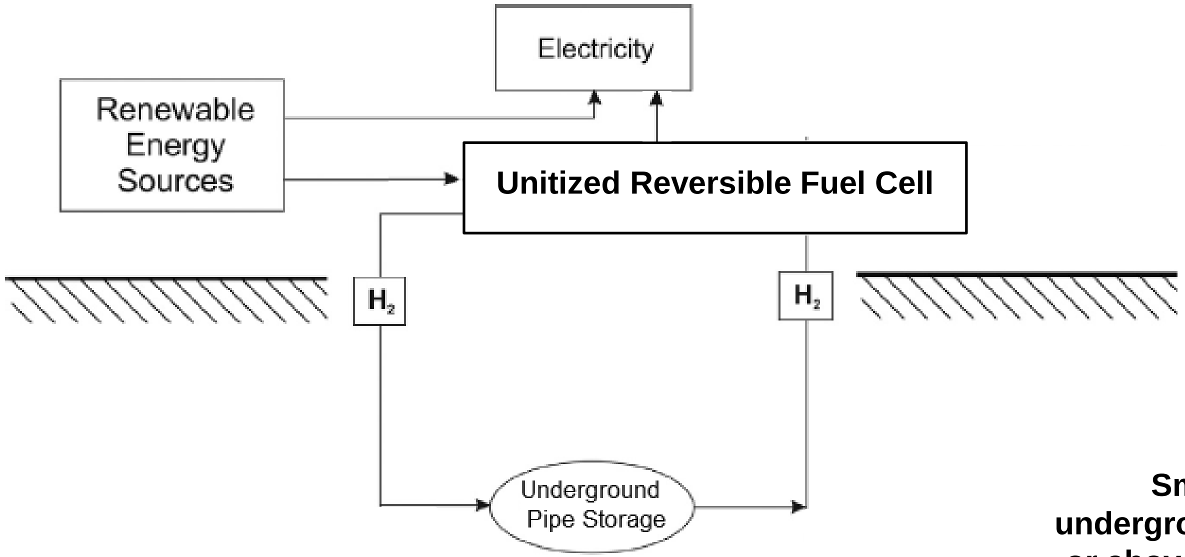
Consolidate Electrolyzer and Fuel Cell to unitized stack for capital cost reduction



Consolidate electrolyzer & fuel cell stack: How much capital cost reduction is possible?

Note on terminology:
"RFC" in this presentation refers to the unitized reversible fuel cell configuration above

Consolidate Electrolyzer and Fuel Cell to unitized stack for capital cost reduction



Note:
Smaller-scale underground pipe storage or above ground storage can be utilized as well, depending on the application

Approach

- Develop Technical Targets for SOFC-RFC and PEM-RFC based on literature review and past cost studies; seek technical inputs from experts to refine targets
- Use LCOS formulation to develop estimates for cost of storage in $/kWhe
- Develop a parametric cost model for RFCs for key design and operating parameters (fuel cell current density, electrolyzer current density, lifetime,capital costs, etc.).
  - Show path/ viability to meet intermediate/long term LCOS target
  - Focus on daily duty cycle with small capacity storage for now; but include some preliminary analysis for long duration storage with larger capacity storage

FY2019 AOP

Qtr'FY	Milestones Description	Status	Go/No-Go Criteria
Q1'19	NA	DONE	
Q2'19	Develop preliminary technical targets for URFC	DONE	
Q3'19	Develop framework for simplified cost analysis	DONE	
Q1'20	Develop updated technical targets for URFC based on expert inputs Preliminary results for parametric cost analysis	DONE	A parametric cost analysis framework for RFCs has been successfully developed and the parametric cost analysis shows sufficient promise for RFCs to proceed with more detailed studies in year 2. RFC parametric cost analysis study should satisfactorily quantify pathway(s) to competitive long term storage for SOFC- or PEM-based RFCs at <=$0.25/kWh LCOS.

Slide on FY20 AOP

Qtr'FY	Milestones Description	Status	Go/No-Go Criteria
Q2 FY20	Develop LCOS estimates with longer duration storage for MW-scale PEM-RFC and SOFC-RFC technologies including multi-parameter sensitivity studies of key parameters (e.g., efficiency, J-V operating point, lifetime)	DONE	
Q3 FY20	Develop parametric LCOS estimates for MW-scale PEM-RFC and SOFC-RFC with refined stack and balance of plant cost estimates for larger system sizes (>1 MW) and key multi-parameter sensitivity analysis (e.g., efficiency, J-V operating point, lifetime)		
Q4 FY20	Develop preliminary parametric cost estimates for PEM-based H2 storage systems with alternative configurations and clarifying discrete vs unitized stacks pros/cons vs operating and other assumptions.		
Q1 FY21	Develop updated parametric cost estimates and multi-parameter sensitivity analysis for PEM-based H2 storage systems with alternative configurations (e.g., discrete vs unitized stacks)		

LCOS – Schmidt/ Apricum formulation adapted

$$LCOS\left[\frac{\$}{MWh}\right]=\frac{\text{Investment cost}+\sum_n^N\frac{\text{O\&M cost}}{(1+r)^n}+\sum_n^N\frac{\text{Charging cost}}{(1+r)^n}+\frac{\text{End-of-life cost}}{(1+r)^{N+1}}}{\sum_n^N\frac{Elec_{Discharged}}{(1+r)^n}}.$$

(Equation 1)

Joule

Oliver Schmidt, Sylvain Melchior, Adam Hawkes, Iain Staffell

Projecting the Future Levelized Cost of Electricity Storage Technologies

$$LCOS=\frac{CAPEX}{\#cycles*DOD*C_{\text{rated}}*\sum_{n=1}^{N}\frac{(1-DEG*n)}{(1+r)^n}}$$
$$+\frac{O\&M*\sum_{n=1}^{N}\frac{1}{(1+r)^n}}{\#cycles*DOD*C_{\text{rated}}*\sum_{n=1}^{N}\frac{(1-DEG*n)}{(1+r)^n}}$$
$$-\frac{\frac{V_{\text{residual}}}{(1+r)^{N+1}}}{\#cycles*DOD*C_{\text{rated}}*\sum_{n=1}^{N}\frac{(1-DEG*n)}{(1+r)^n}}$$
$$+\frac{P_{\text{elec-in}}}{\eta(DOD)}$$

With:

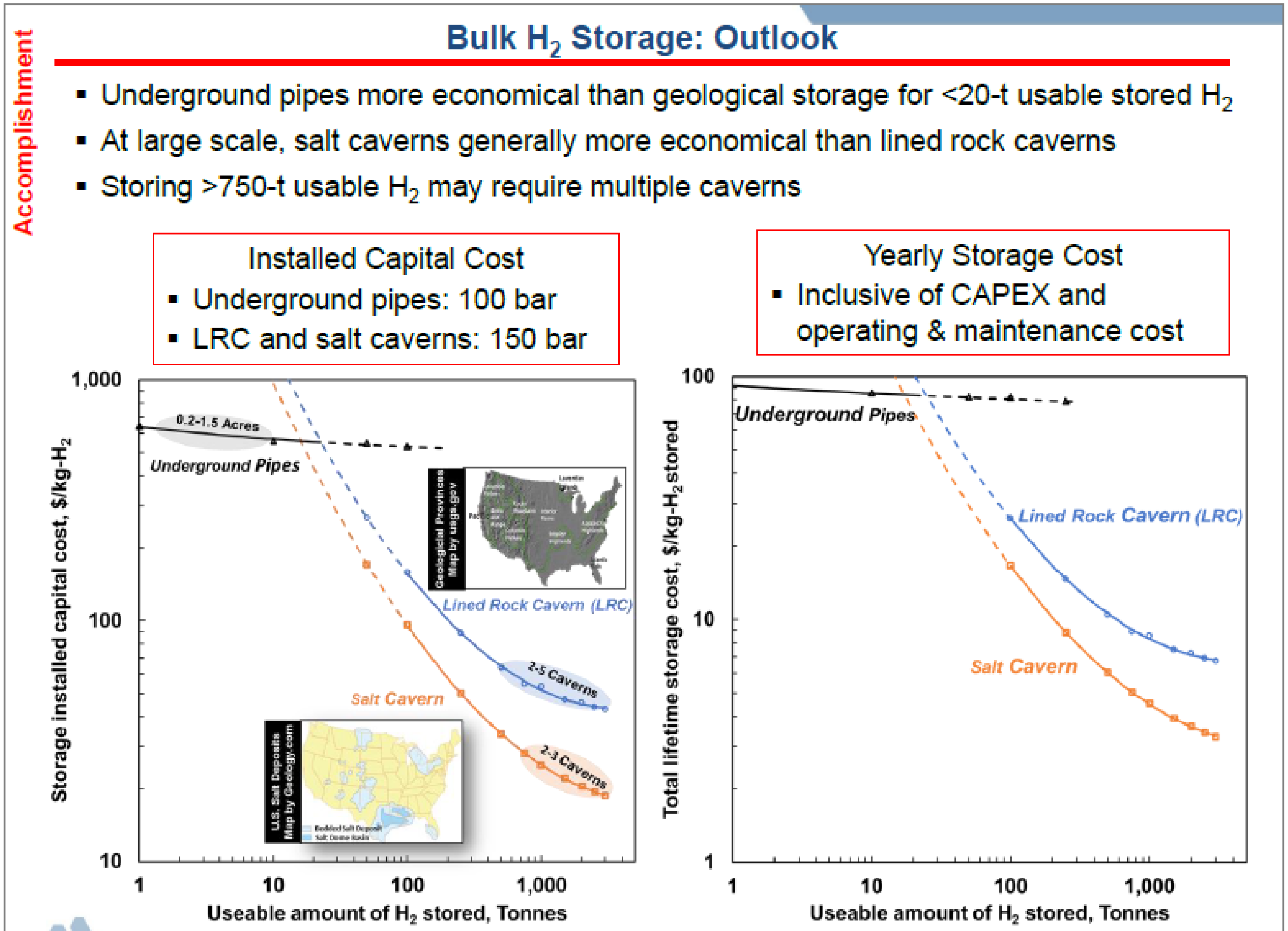
$\#cycles$	= full charging/discharging cycles per year
DOD	= depth of discharge
C_{rated}	= rated capacity
DEG	= annual degradation rate of capacity[1]
N	= project lifetime in years
r	= discount rate (e.g., weighted average cost of capital)
$O\&M$	= O&M cost (assumed to be constant)
V_{residual}	= residual value (after project lifetime)
$P_{\text{elec-in}}$	= charging electricity tariff (assumed to be constant)
$\eta(DOD)$	= round-trip efficiency at *DOD* (assumed to be constant)

1) Assuming linear degradation

More detailed formulation (Apricum 2016)

Storage cost, this work

- Take Storage cost values from literature [Ahluwalia 2019 AMR + other literature (Sandia, Tarkowski 2017, etc.)]
- E.g., Cap costs~ $600/kg H2 to $20/kg subsurface below



Ahluwalia 2019

Accomplishments and Progress

Technical targets established

- In conjunction with DOE FCTO, technical targets were established for PEM-RFC and SOFC-RFC
- Reviewed by team of 14 experts from industry/academia/national labs

PEM RFC Technical Targets

Characteristic	Units	2020 Status	2030 Targets	Ultimate Targets
Cell Performance/Roundtrip Electrical Efficiency at 0.5 A/cm^2 Fuel Cell; 1 A/cm^2 Electrolyzer	%	52	55	65
Cell Durability/Degradation Rate,	%/1000 hr	-	0.25	0.125
Total Cell Platinum Group Metal Loading	mg/cm^2	1.3[3]	1.0	0.5
Stack Capital Cost (Based on Fuel Cell Power Output)	$/kW,	1000	550	300
System				
System Roundtrip Efficiency	%	-	40	50
Lifetime/Durability,	hr [Cycles]	-	40,000 [1667]	80,000 [3333]
Levelized Cost of Storage	$/kWh	1.60	0.20	0.10[11]
System Capital Cost by Power	$/kW	-	1750	1250
System Capital Cost by Energy	$/kWh	-	250	150

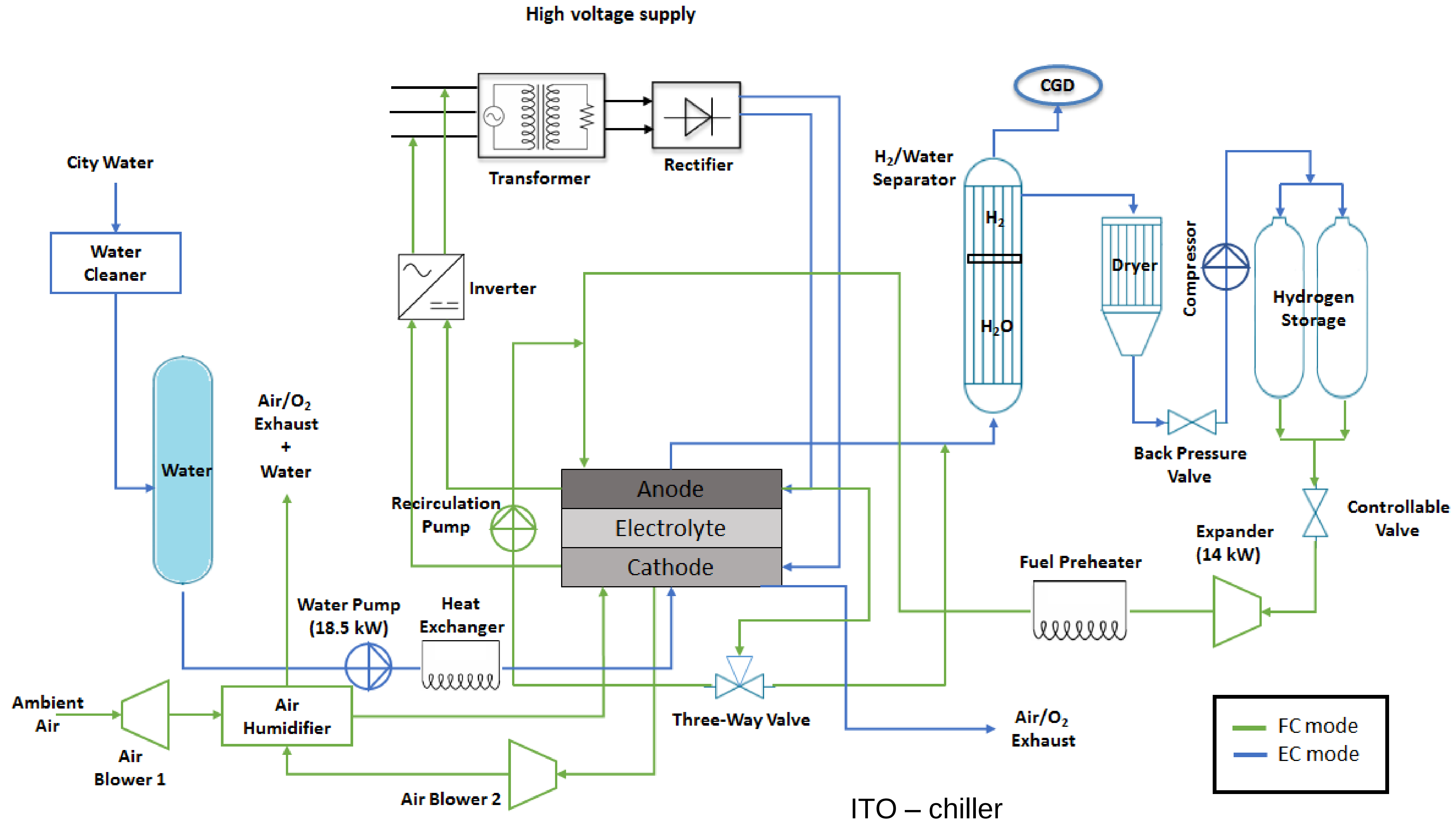
Technical targets established

- In conjunction with DOE FCTO, technical targets were established for PEM-RFC and SOFC-RFC
- Reviewed by team of 14 experts from industry/academia/national labs

SOFC RFC Technical Targets

Characteristic	Units	2020 Status	2030 Targets	Ultimate Targets
Cell Performance/ Roundtrip Electrical Efficiency at 0.5 A/cm2 FC; 1 A/cm^2 EL	%	80	80	85
Cell Durability/Degradation Rate,	%/1000 hr	<1.5	0.25	0.125
Stack Capital Cost (based on FC power output)	$/kW	500	330	300
System				
System Roundtrip Efficiency	%	-	40	50
Roundtrip System Efficiency (includes thermal energy input)	%	37	60	70
Lifetime/Durability,	hr [Cycles]	10,000[7] [unknown]	40,000 [1667]	80,000 [3333]
Levelized Cost of Storage	$/kWh	1.11	0.20	0.10[11]
System Capital Cost by Power	$/kW	-	$1750	$1250
System Capital Cost by Energy	$/kWh	-	250	150

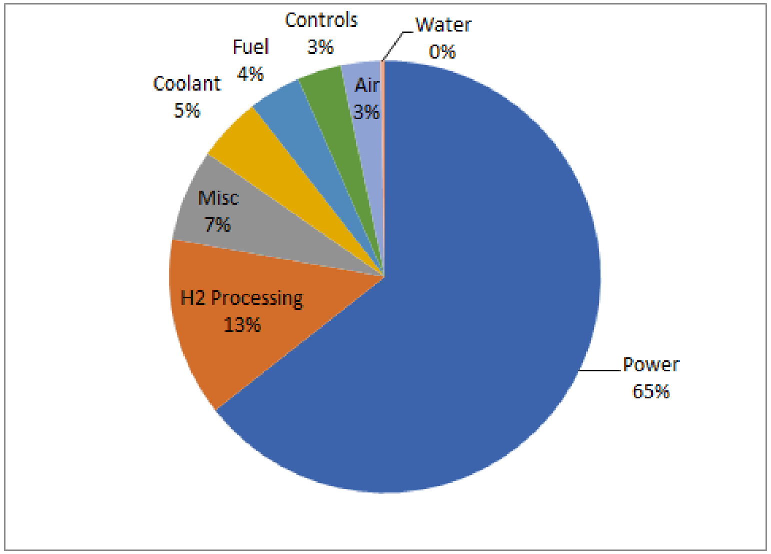
PEM-RFC System Schematic (250kW FC)



ITO – chiller

O2/ water separator – H2O circulation loop

PEM-RFC Balance of Plant Costs - Power electronics, H2 processing dominate



BOP VOLUME - Stationary	250				
Production Units		100	1000	10000	50000
Subsystem 1: Fuel	Hydrogen Expander (pressure regulator)	$ 1,920	$ 1,536	$ 1,229	$ 983
	Recirculation Pump (H2 recirculation)	$ 1,752	$ 1,402	$ 1,121	$ 897
	Fuel Preheater	$ 10,092	$ 8,074	$ 6,459	$ 5,167
	Total	$ 13,765	$ 11,012	$ 8,809	$ 7,048
Subsystem 3: Hydrogen Processing	Hydrogen/Water Separator	$ 9,985	$ 7,988	$ 6,391	$ 5,113
	Dryer	$ 13,845	$ 11,076	$ 8,861	$ 7,088
	Hydrogen Compressor	$ 17,881	$ 14,305	$ 11,444	$ 9,155
	Valves and instrumentations	$ 4,851	$ 3,880	$ 3,104	$ 2,483
	Total	$ 46,562	$ 37,249	$ 29,799	$ 23,840
Subsystem 4: Air	Air Piping	$ 3,637	$ 2,910	$ 2,328	$ 2,072
	Air Humidifier Tank	$ 1,538	$ 1,196	$ 1,025	$ 855
	Humidification Pump	$ 700	$ 560	$ 448	$ 399
	Radiator	$ 612	$ 544	$ 517	$ 232
	Manifolds	$ 1,344	$ 844	$ 844	$ 844
	Total	$ 9,137	$ 7,150	$ 6,117	$ 5,306
Subsystem 5: Coolant	Coolant Tank	$ 2,130	$ 1,656	$ 1,420	$ 1,183
	Coolant Pump Motor	$ 1,457	$ 1,165	$ 932	$ 830
	Coolant Piping	$ 2,425	$ 1,940	$ 1,552	$ 1,381
	External Cooling Fan/ Motor	$ 6,289	$ 5,683	$ 5,152	$ 5,152
	Total	$ 12,300	$ 10,444	$ 9,056	$ 8,546
Subsystem 6: Power System	Power Inverter	$ 77,068	$ 61,655	$ 49,324	$ 39,459
	Rectifier	$126,720	$101,376	$ 81,101	$ 64,881
	Transformer	$ 866	$ 693	$ 554	$ 493
	Braking Transistors	$ 2,364	$ 1,891	$ 1,513	$ 1,347
	Switches	$ 1,773	$ 1,418	$ 1,134	$ 1,010
	Fuses	$ 658	$ 526	$ 421	$ 375
	HMI (human-machine-interface)	$ 1,678	$ 1,342	$ 1,074	$ 956
	Bleed Resistor	$ 743	$ 594	$ 476	$ 423
	Voltage Transducer	$ 5,007	$ 4,006	$ 3,204	$ 2,852
	Power Cables (2W and 4W)	$ 3,993	$ 3,194	$ 2,555	$ 2,274
	Total	$222,089	$177,671	$142,137	$114,764
Subsystem 7: Controls/Meters	Variable Frequency Drive	$ 3,074	$ 2,459	$ 1,967	$ 1,751
	CPU	$ 1,151	$ 1,082	$ 981	$ 785
	Pressure Transducer	$ 775	$ 620	$ 496	$ 441
	Temperature Sensors	$ 3,349	$ 2,679	$ 2,143	$ 1,907
	Hydrogen Sensors/Transmitter and Controller	$ 691	$ 553	$ 442	$ 394
	Sensor Head	$ 727	$ 582	$ 466	$ 414
	Total	$ 10,032	$ 8,186	$ 6,665	$ 5,843
Subsystem 8: Misc. Components	Tubing	$ 1,858	$ 1,486	$ 1,189	$ 1,058
	Enclosure	$ 7,882	$ 6,305	$ 5,044	$ 4,489
	Fasteners	$ 1,156	$ 924	$ 740	$ 658
	Labor Cost	$ 19,000	$ 11,000	$ 5,500	$ 5,500
	Total	$ 30,902	$ 20,522	$ 13,117	$ 12,279
	Total BOP cost [$/system]	$345,909	$273,133	$216,420	$178,200
	Total BOP cost [$/kW]	$ 1,384	$ 1,093	$ 866	$ 713

PEM-RFC LCOS

Cap cost for power unit

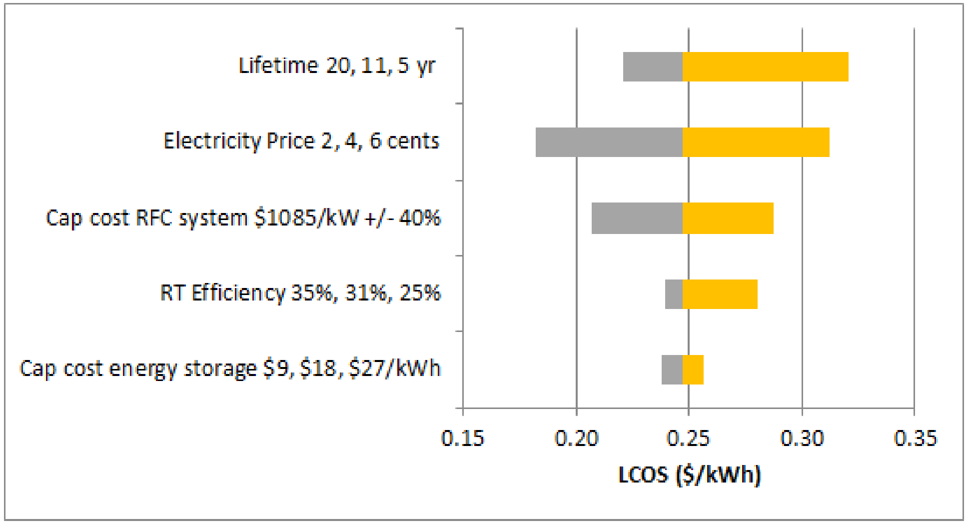
250kW				
Units/yr	100	1,000	10,000	50,000
Stack cost $/kW	667	502	419	372
BOP cost $/kW	1,384	1,093	866	713
Syst cost $/kW	2050	1595	1284	1085

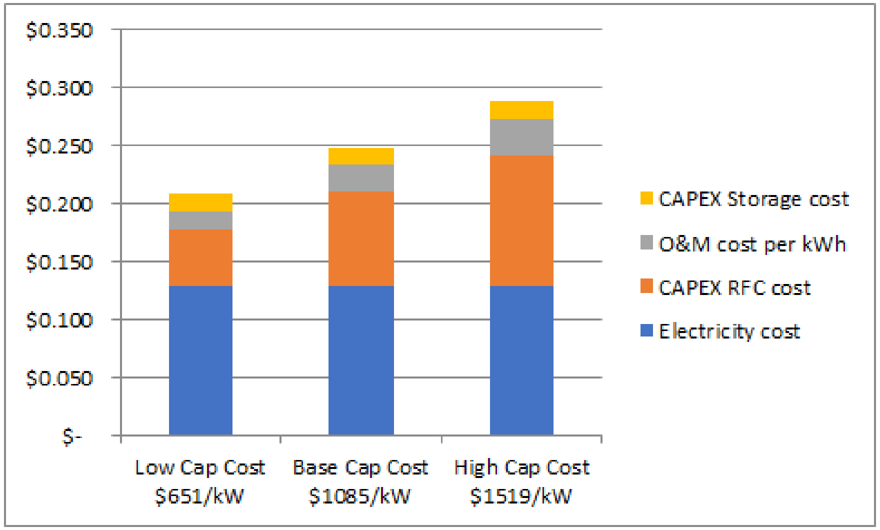
- **Path to $0.25/kWh and lower LCOS established:**
  - High annual volume (cap costs above)
  - Reduce material costs and PGM loading (Intermediate PGM loading here 1mg/cm2)
  - Low cost electricity, 4.0 cents/kWh electricity here
  - Improved lifetime (11 year lifetime here)
  - Further reductions from lifetime, capital cost, and efficiency

LCOS

INPUT PARAMENTERS		
O&M	3.5%	*% of capital cost*
Installation costs + "soft costs"	33%	*% of capital cost*
Hydrogen Storage Capital cost by energy	18	[$/kWh] -->
Capital cost by power	1085	[$/kW] -->
Electricity price	0.04	[$/kWh]
RTE	31%	[%]
FC-Efficiency	48%	[%]
EC-Efficiency	65%	[%]
Charge hours	10	[h/day]
Discharge hours	8	[h/day]
Stand-by hours	-	[h/day]
num cycles	350	[cycles/year]
n	11	[years]
i	8%	[%]
Power FC	250	[kW]
Power EC	591	[kW]
CALCULATED PARAMETERS		
C input (EC)	6470	[kWh]
C storage	3078	[kWh]
C rated	2000	[kWh]
System capital cost	$ 470,437	[$]
Maintenance costs	$ 16,465	[$]
LEVELIZED COST OF STORAGE		
LCOS	0.247	[$/kWh]

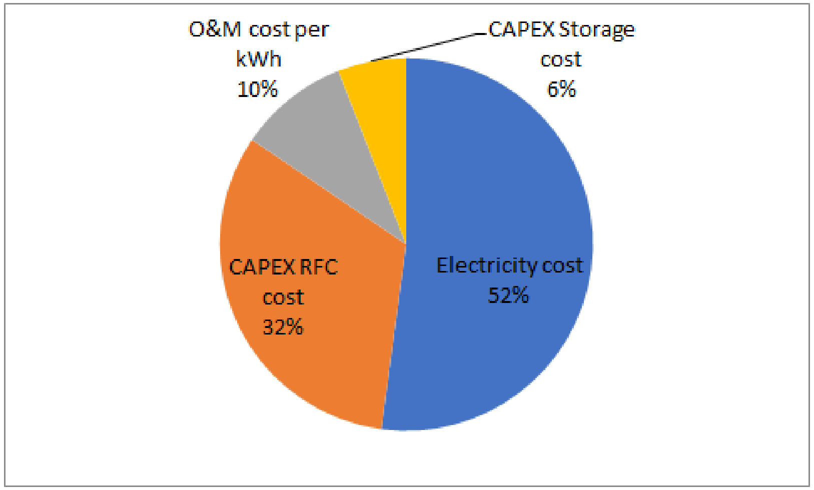
Sensitivity for PEM-RFC from $0.247/kWh base & Stack Plot of Cost Components vs Cap Cost





Lifetime, electricity price, RFC capital cost are sensitive parameters starting from a $0.247/kWh reference

Base cap cost: Electricity cost is 52% of LCOS (rt)

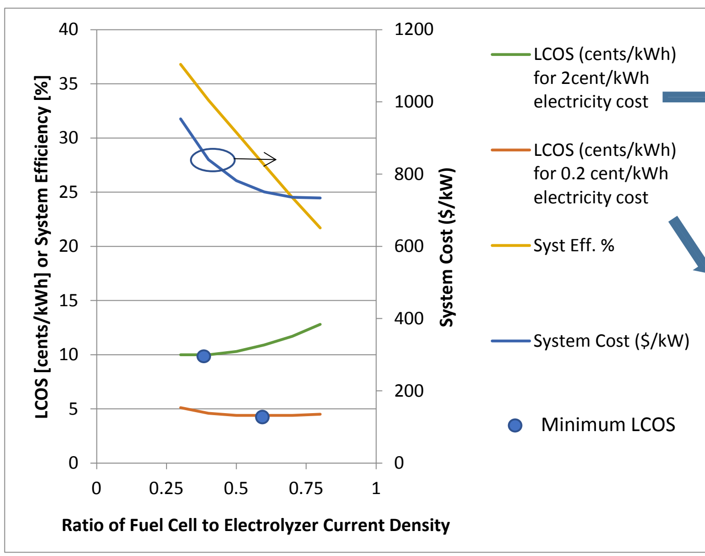


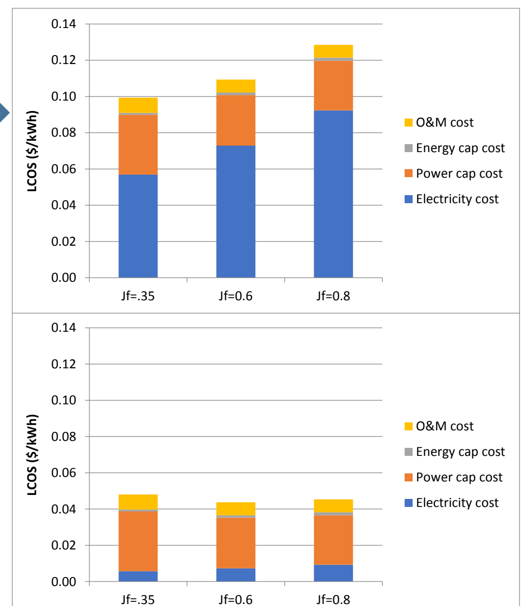
Achieving the ultimate target, PEM-RFC

Achieving $0.10/kWh and below LCOS

- Need very low cost electricity $0.002 - $0.02/kWh, i.e. very high renewables grid (>80% solar, wind)
- High quantity of discharge hours (5600 hrs here)
- Round trip efficiency > ~30%, 10 year lifetime
- Cap cost < $1000/kW (from high volume and BOP consolidation)
- H2 storage cost < $1/kWh (e.g., subsurface storage)

- Min. cost design point a tradeoff of capital costs, system efficiency, and electricity cost (bottom left figure)
- Can achieve less than 5 cents/kWh with these assumptions



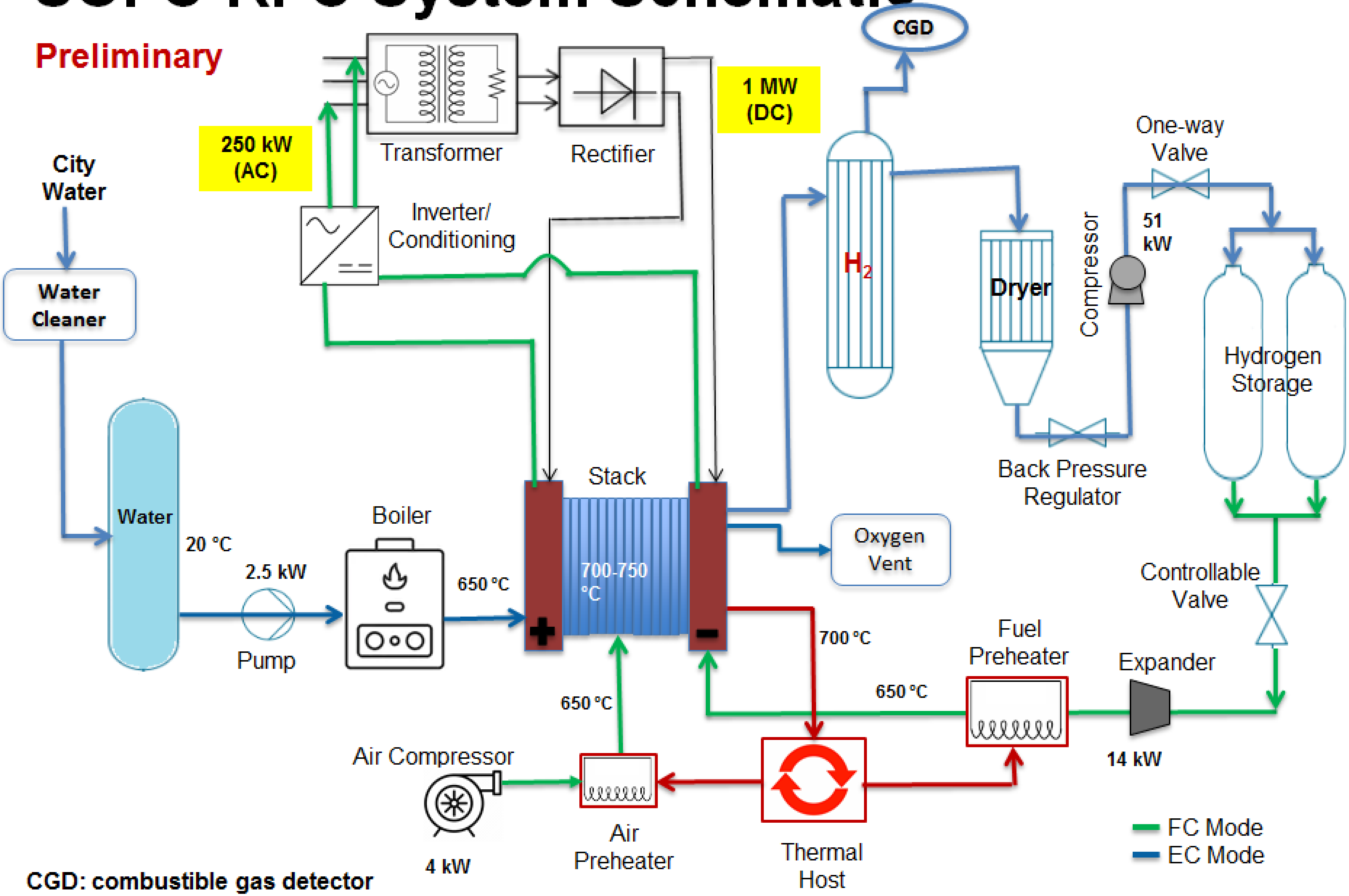


INPUT PARAMENTERS		
O&M	3.5%	*% of capital cost*
Installation costs + "soft costs"	33%	*% of capital cost*
Hydrogen Storage Capital cost by energy	1	[$/kWh] -->
Capital cost by power	840	[$/kW] -->
Electricity price	0.002	[$/kWh]
RTE	34%	[%]
FC-Efficiency	49%	[%]
EC-Efficiency	68%	[%]
Charge hours	7.0	[h/day]
Discharge hours	16.0	[h/day]
Stand-by hours	-	[h/day]
num cycles	350	[cycles/year]
DOD	100%	[%]
DEG	0%	[%]
Efficiency degradation	9%	[%/year]
n	10.00	[years]
i	7%	[%]
Power FC	250	[kW]
Power EC	1530	[kW]

CALCULATED PARAMETERS		
C input (EC)	11923	[kWh]
C storage	8108	[kWh]
C rated	4000	[kWh]
System capital cost	$ 317,903	[$]
Maintenance costs	$ 11,127	[$]
Total cap cost quoted in units of $/kW	$ 1,272	$/kW
Total cap cost quoted in units of $/kWh	$ 79	$/kWh

LEVELIZED COST OF STORAGE		
LCOS	0.046	[$/kWh]

SOFC-RFC System Schematic



CGD: combustible gas detector

SOFC-RFC LCOS

Cap cost for power unit

250kW				
Units/yr	100	1,000	10,000	50,000
Stack cost $/kW	500	330	300	300
BOP cost $/kW	1,896	1,498	1,183	970
Syst cost $/kW	2,396	1,828	1,483	1,270

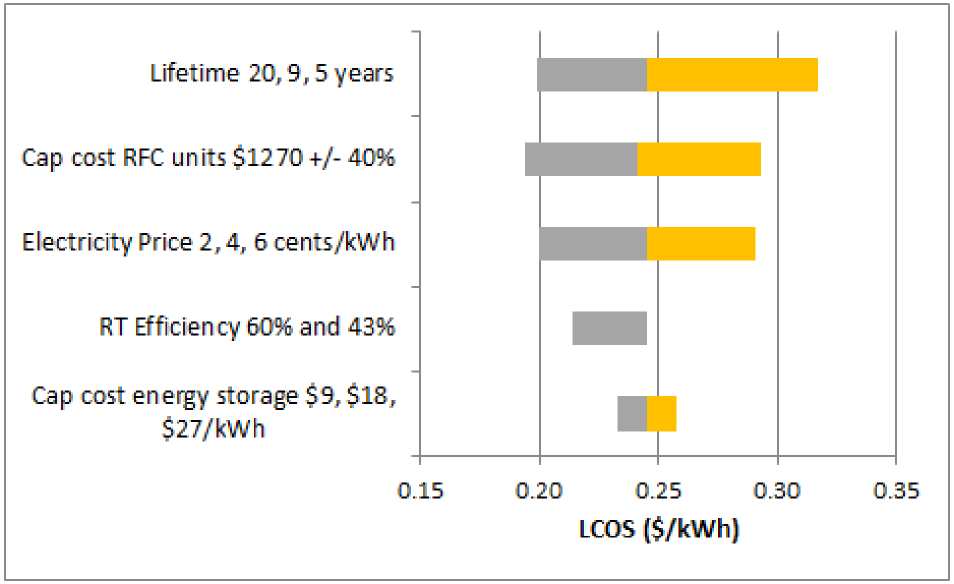
Path to $0.25/kWh and lower LCOS:

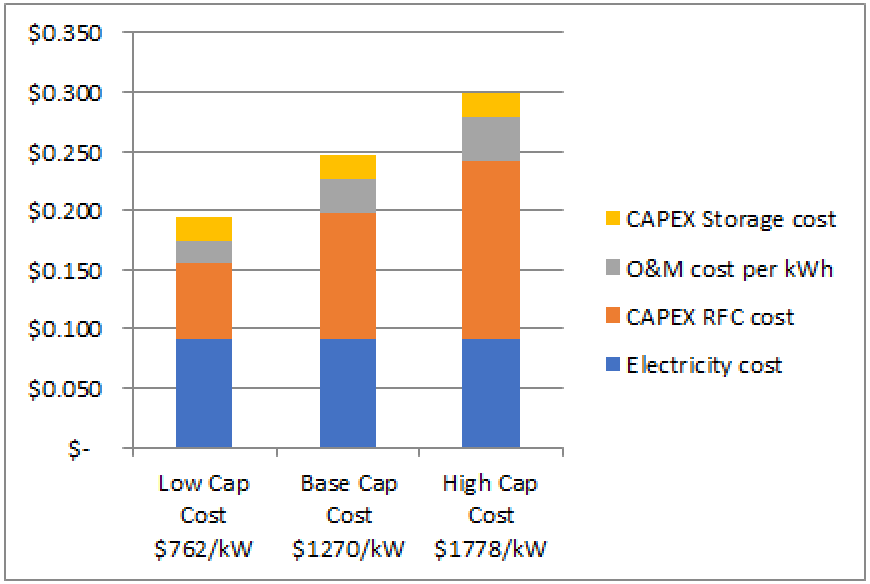
- High annual volume (cap costs above)
- 9 year lifetime assumed here
- Low cost electricity, 4.0 cents/kWh here
- Further reductions from efficiency, lifetime, and capital costs

LCOS

INPUT PARAMETERS		
O&M	3.5%	*% of capital cost*
Installation costs	33%	*% of capital cost*
Capital cost for hydrogen storage	18	[$/kWh] -->
Capital cost for power unit	1270	[$/kW] -->
Electricity price	0.040	[$/kWh]
RTE	44%	[%]
FC-Efficiency	53%	[%]
EC-Efficiency	83%	[%]
Charge hours	10	[h/day]
Discharge hours	8	[h/day]
num cycles	350	[cycles/year]
n	9.0	[years]
i	8%	[%]
Power FC	250	[kW]
Power EC	454	[kW]
CALCULATED PARAMETERS		
C input (EC)	4541	[kWh]
C storage	3780	[kWh]
C rated	2000	[kWh]
System capital cost	$ 554,990	[$]
Maintenance costs	$ 19,425	[$]
LEVELIZED COST OF STORAGE		
LCOS	0.245	[$/kWh]

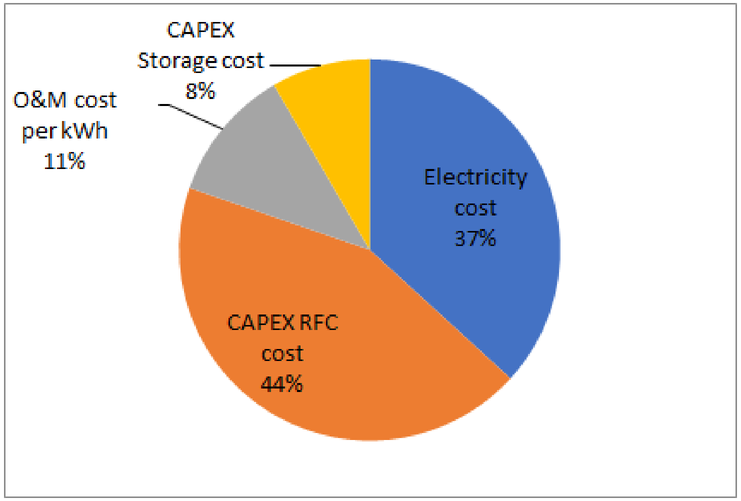
Sensitivity for SOFC-RFC from $0.245/kWh base and Stack Plot of Cost Components vs Cap Cost





Lifetime, Cap cost for RFC, Electricity price are are sensitive parameters starting from a $0.245/kWh reference

Base cap cost: Electricity cost is 37% of LCOS (rt)



Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

- No reviewer comments last year (1^{st} year of project)

Collaboration and coordination

- In year 1, NREL contributed in several ways:
  - SOFC system design and functional specifications development
  - Provided expert inputs on PEM electrolyzer cost components which were key inputs to the costing analysis
  - Shared high renewables grid modeling output for long duration storage
- For development of technical targets, technical inputs from technical experts were coordinated with DOE FCTO Golden office

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Remaining Challenges and Barriers

- Determining duty cycles for very high renewable penetrations
- Determining realistic lifetime, cycle life for u-RFC technology
- Determining cost requirements for long duration applications
- BOP consolidation e.g., bi-directional inverters (inverter+ rectifier) market readiness

Proposed Future Work

- Further develop range of use cases including daily to seasonal storage and variable duty cycles through the year; in consultation with DOE FCTO and NREL grid modeling group (e.g. NREL 85% renewable energy grid modeling from past fiscal year)
- Coordinate with other PEM-RFC experimental projects at LBNL and DOE for latest data on lifetime testing and stack designs to further refine material & cost analysis of PEM-RFC and SOFC-RFC stacks
- Scale cost estimates to at least MW-scale for PEM-RFC and SOFC-RFC (leverage parallel MW-scale H2 PEMFC cost analysis at LBNL)
- Determine potential for further BOP simplification/consolidation – one focus is on cost reduction from bi-directional inverters and industry outreach on this topic
- Quantify cost reduction possible for systems with lower cycles and hours of operation
- Consider cases of energy storage only and storage for grid + sale of excess H2
- Investigate alternative system configurations e.g., discrete vs unitized stacks for PEM and system optimization for different use cases
- Conduct key multi-parameter sensitivity studies for both PEM-RFC and SOFC-RFC

Any proposed future work is subject to change based on funding levels

Technology Transfer Activities

Include any technology-to-market or technology transfer plans or strategies that you have for the technology

- NA

Include plans for future funding from alternative sources as well as marketing strategies and options

- Pursue technology demonstration and further techno-economic analysis in California through California funding agencies

Include any patent, licensing, or potential licensing information.

- NA

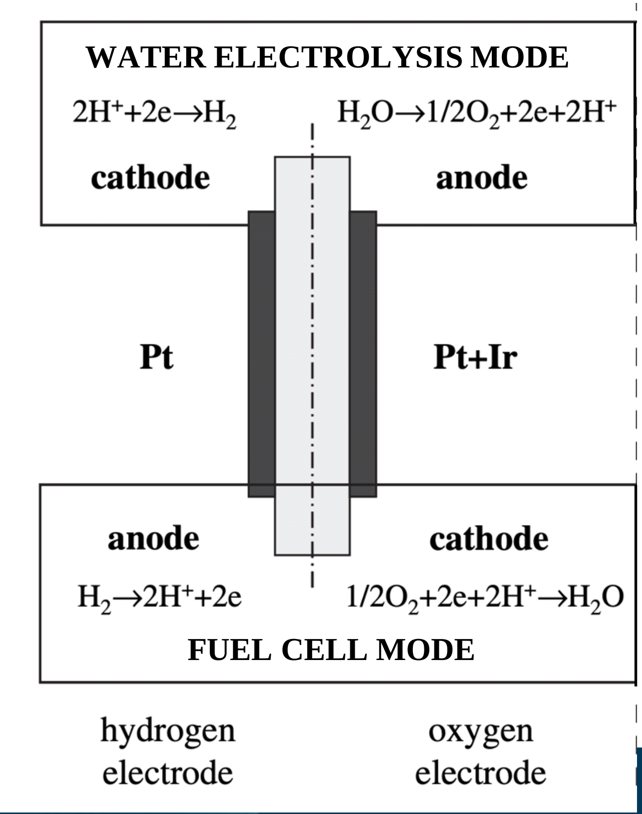
Summary

- RFC technical targets for PEM and SOFC have been generated and finalized per expert review
- A framework has been developed for parametric cost analysis of PEM-RFC and SOFC-RFC
- Path to <$0.10/kWh shown for PEM-RFC. For further cost reduction,
  - Need high volume, efficiency gains, longer lifetime, lower system cost for PEM-RFC
  - Need high volume, efficiency gains, lower BOP cost for SOFC-RFC
- Year 2 focus areas: expand duty cycle to include longer duration storage; further develop cost reduction approaches and analysis; and characterize least cost system designs vs end use application

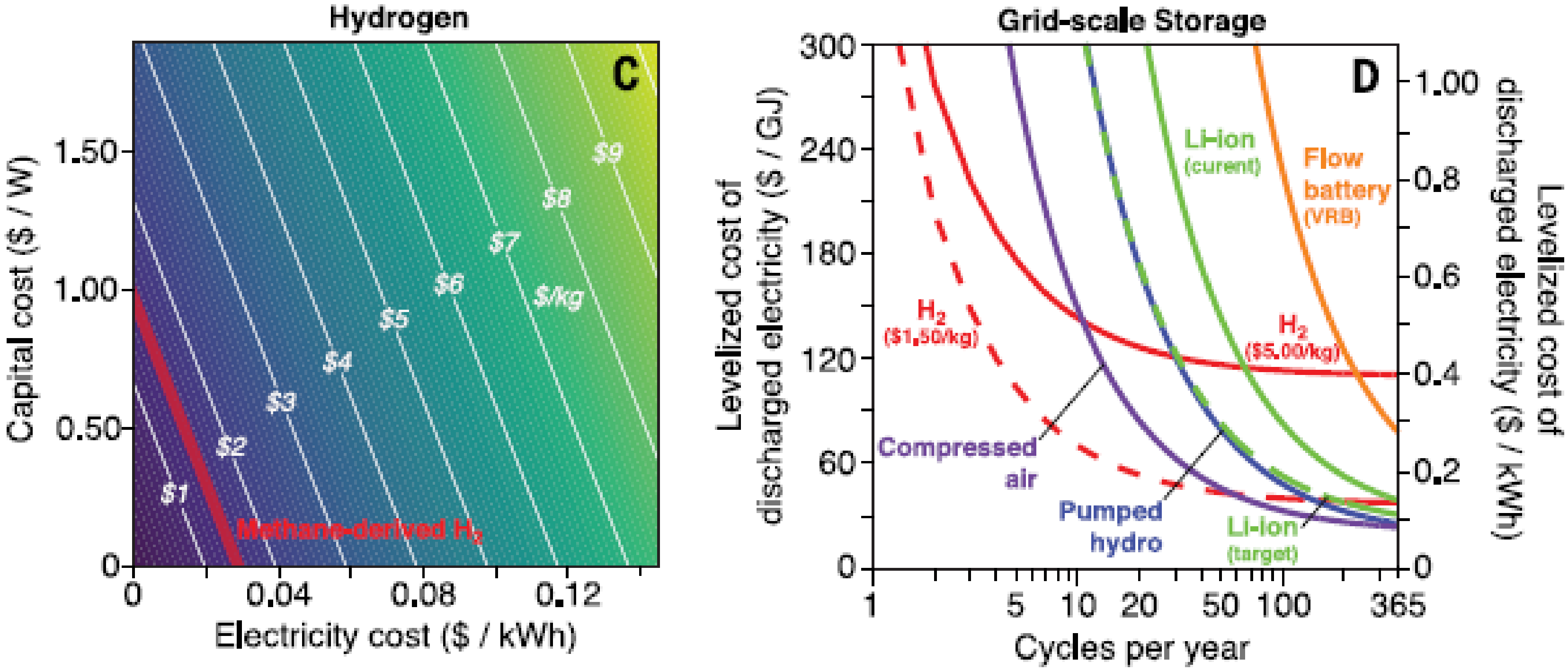
Technical Backup Slides

What is a Unitized Reversible Fuel Cell?

A **unitized reversible fuel cell (U-RFC)** is a device that combines two modes of operation or bi-directionality in one stack of electrochemical cells – a fuel cell and an electrolyzer. The uRFC architechture can potentially save on capital costs of equipment, but must be carefully engineered to meet performance and lifetime goals.



Levelized cost of electricity from H2 storage more competitive for longer duration storage and H2<$1.50/kg (<$1000/kW capital, <$0.03/kWh electricity costs)



Davis et al., Science 360, eaas9793 (2018)

How might ~$1000/kW capital cost be achieved for long duration storage?

PEM-RFC

- Stack parameters below

	Fuel Cell	Electrolyzer	Units
Stack power	250	591	kW
Total plate area	363	363	cm^2
CCM coated area	306	306	cm^2
Single cell active area	285	285	cm^2
Gross cell inactive area	21%	21%	%
Cell amps	71	71	A
Current density	0.40	1.00	**A/cm^2**
Reference voltage	0.71	1.73	**V (cell voltage)**
Power density	0.282	1.728	W/cm^2
Single cell power	80	492	W
Cells per stack	124	124	cells
Cells per system	3106	3106	cells
Stacks per system	25	25	stacks
Stack Voltage Efficiency	57%	71%	%
Total parasitics	35	61	kW
Net syst. Electrical efficiency	49%	68%	%
Total system efficiency	33.5%		%

SOFC-RFC

- Stack parameters below

	Fuel Cell Mode	Electrolyzer Mode	Units
Stack power	250	454	kW
Total plate area	540	540	cm^2
Electrode area	329	329	cm^2
Single cell active area	299	299	cm^2
Gross cell inactive area	45%	45%	%
Single cell amps	132	132	A
Current density	**0.44**	**0.44**	**A/cm^2**
Reference voltage	**0.71**	**1.29**	**V (cell voltage)**
Power density	0.312	0.568	W/cm^2
Single cell power	93.4	169.7	W
Cells per system	2676	2676	cells
Stacks per system	21	21	cells
Cells per stack	127	127	stacks
Stack Voltage Efficiency	58%	95%	%
Net electrical efficiency	53%	83%	kW
Round trip system efficiency	44%		%

Task 2: Approach

Bulk H_2 Storage Methods

NG Spherical Pressure Vessel, Germany

NG Pipe Storage, Erdgas, Switzerland

LH_2 Cryogenic Storage, NASA

FY 2019 Work
- Pipe storage, salt cavern, lined rock cavern

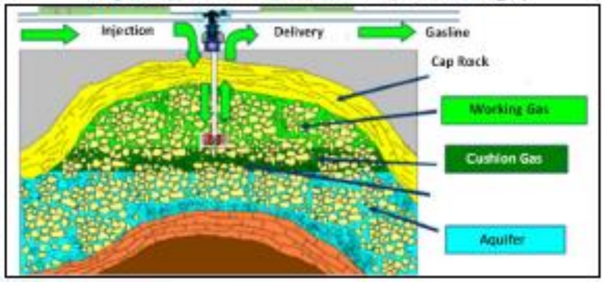
Future Work
- Forecourt, cryogenic

	Pressure Vessels				Cryogenic	Geologic Storage		
	Spherical Vessels	Pipe Storage	Pre-stressed Concrete	WireTough		Aquifer	Salt Cavern	Lined Rock Cavern
Pressure, bara	1-10.4	7-100	7-875	7-875	20	150-170	55-152	10-230
Diameter, m	39.5	1.4	2.2	0.43	20			35
Wall Thickness, mm	34		110					6-12
Length, m		200 (13x15)		9.2				
Depth, m						1,500	1,200	115
Height, m			5.3					52
Water Volume, m^3	32,000	6,100	22	0.77	3400	4,141,000	566,000	40,000
Net Volume (STP), m^3	273,664	500,556	10,979	428	2,558,399	211,346,012	41,379,324	7,119,024
H_2 Stored, t	27	50	1	0.0389		54,000	6,000	672
Working Capacity, t	24.6	45	0.987	0.0385	230	19,000	3,720	640
Application		City Gate	Forecourt	Forecourt	City Gate Forecourt		City Gate	City Gate

Salt Cavern, H_2 Storage, Praxair, Texas

Rock excavation (dome), Skallen,

Aquifer, Stenlille, Denmark (NG storage)



See slide 30 for references